Radiance in a Dynamic Ocean (RaDyO): Radiance and Visibility as Affected by Inherent Optical Properties

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LONG-TERM GOALS

The long-term goal of "Radiance in a Dynamic Ocean (RaDyO): Radiance and Visibility as Affected by Inherent Optical Properties" is to perform detailed investigations of inherent optical properties (IOPs) and the effects of IOP variability on underwater radiance and visibility. As part of this effort, Sea Engineering, Inc. (SEI) will also provide all data from the Scripps Pier and Santa Barbara Channel (SBC) RaDyO experiments to the ONR and to all other RaDyO investigators, with a detailed report describing the technical approach and algorithms used for data processing.

OBJECTIVES

The primary objectives of the Radiance in a Dynamic Ocean (RaDyO) program are to:

1) Examine time-dependent oceanic radiance distribution in relation to dynamic surface boundary layer (SBL) processes.
2) Construct a radiance-based SBL model.
3) Validate the model with field observations.
4) Investigate the feasibility of inverting the model to yield SBL conditions.

As part of the RaDyO project, SEI will perform RaDyO IOP data processing and analysis including data sharing with other RaDyO PIs. Data post-processing includes application of field-calibrations, corrections for temperature, salinity, and scattering effects, and comparisons with similar IOP data collected by RaDyO collaborators.

IOP data analysis as related to the RaDyO program will include detailed investigations of the differences, if any, between optical properties and optical variability measured off the R/P FLIP and off the R/V Kilo Moana (KM) during the RaDyO SBC experiment and the effects of optical variability on the modeling of the underwater radiance distribution and visibility.

APPROACH

The technical approach for the Scripps Pier and SBC experiments involved the use of a ship-based optical profiler package with the following sensors: SeaBird Electronics, Inc. conductivity-

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temperature-depth (CTD) (SBE49), WET Labs, Inc. ac-s (86- or 87-wavelengths), ac-9 (with 0.2 μm filter), bb-9, ECOFL-NTU, and Sequoia Scientific, Inc. LISST-100X Type C (Figures 1-4).

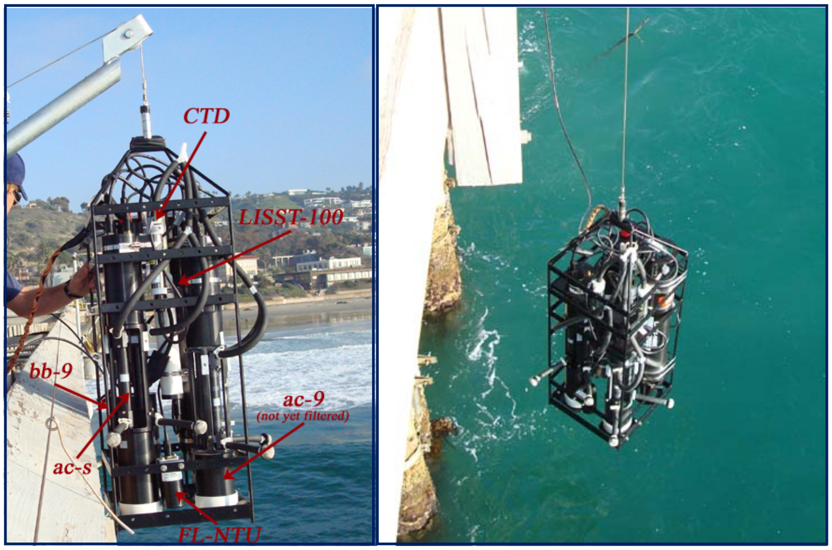

Figure 1. Photographs of the optical profiling package in operation at Scripps Pier in January 2008. Individual sensors are labeled in the photograph on the left.

Our objectives for the Scripps Pier experiment were to:
(1) Ensure all gear is working properly,
(2) Work toward integration of instruments/measurement approaches,
(3) Determine what is missing,
(4) Meet RaDyO science objectives for shallow waters.

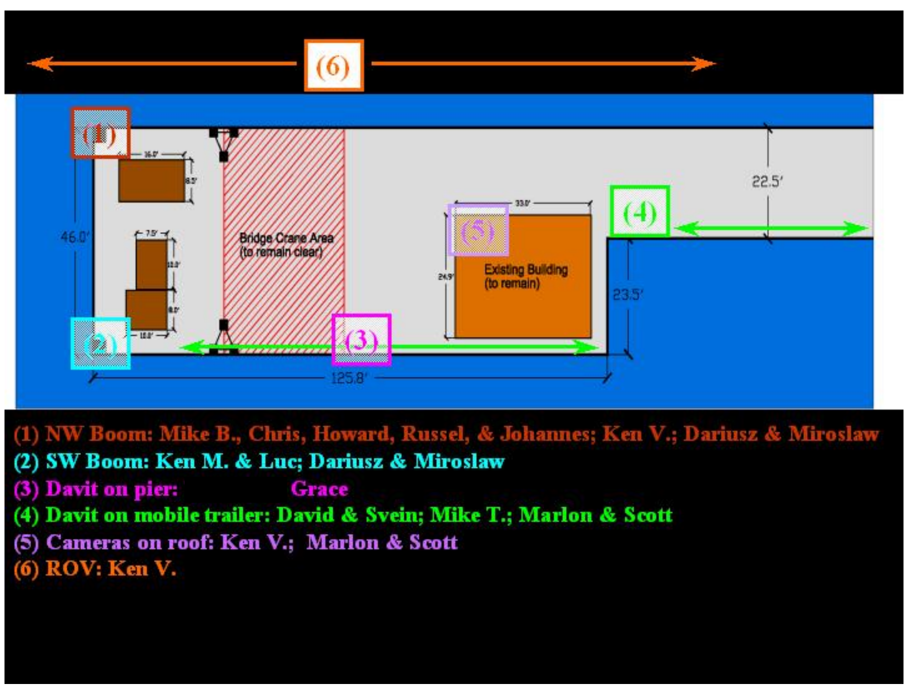

Figure 2. Schematic diagram of Scripps Pier and approximate locations of sampling by RaDyO PIs.

Data collection during the Scripps Pier experiment was from 14 to 24 January 2008. Our optical profiler was operated from a portable davit and winch system off the south side of the pier, next to the bridge crane area (Figures 1 and 2). The depth of data collection ranged between 4 and 7 m, depending on tidal conditions. Profiles were taken on average five times per day between 1000 and 1600 local time (Pacific Standard Time, PST) except one period of night time sampling, performed in conjunction with L. Lenain's (Scripps Institution for Oceanography, SIO) "Cadillac" data collection. The winch was hand-operated at roughly 10 min per 6 m up- and downcasts. Optical sensors were calibrated with pure water at the end of the day, every other day during the course of the experiment, following manufacturer recommended protocols and improvements suggested by M. Twardowski and Scott Freeman (WET Labs, Inc.) and A. Whitmire (Oregon State University). Calibration files were saved and applied during data processing. The participants were: F. Spada, F. Nencioli (University of California, Santa Barbara), G. Chang, and A. Whitmire.

The objective of the SBC experiment was to meet RaDyO science objectives for benign conditions (low winds and small waves).

SBC data were collected off the R/P FLoatIng Platform (FLIP) between 11 and 20 September 2008. The location of the FLIP was 34° 12.312'N, 119° 34.715'W (Figure 3). Due to the malfunction of the port boom and resulting lack of available wire time on the FLIP, our optical profiler was operated from the face boom between 11 and 14 September and then from the starboard boom on the 17th and 20th of September (Figure 4). During face boom sampling, profiles were coordinated with WET Labs, Inc. MASCOT package sampling periods (off the R/V Kilo Moana, KM). Deep profiles were collected at about 1230 and 1600 local time (Pacific Daylight Time, PDT). Casts were taken to 30 m over a 20 minute sampling period. The optical profiler was left in-water between casts and shallow (2 m) time series were collected for 10 minutes every hour between deep casts. Starboard boom sampling consisted of only deep casts at time periods when FLIP crew members were available to assist in data collection. These deep casts were also to 30 m, over 45 minute sampling periods. Note that pure water calibrations were not performed during the SBC experiment due to lack of personnel on-board the FLIP. Calibrations were done just prior to and following the experiment period; these files and those collected during the Scripps Pier experiment were applied during SBC data processing.

Figure 3. Map of the Santa Barbara Channel, CA with locations of the R/V Kilo Moana (blue cross) and R/P FLIP (red dot) indicated.

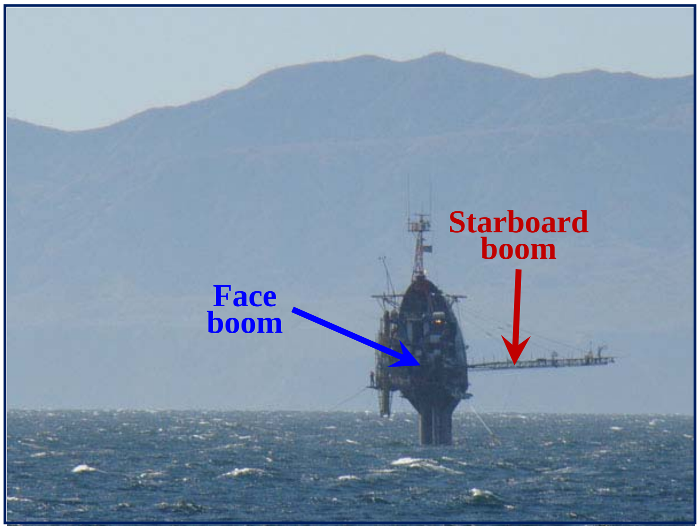

Figure 4. Photograph of the FLIP in the SBC on 19 September 2008 with the face boom and starboard booms indicated. Santa Cruz Island can be seen in background. Photo by Frank Spada

In addition to the optical profiler, an instrumentation package was mounted on the hull of the FLIP, at 30 m. The sensors on the package included: WET Labs, Inc. ac-s, ECObb-3, and Water Quality Monitor (WQM). The WQM provides time series of temperature, salinity, chlorophyll fluorescence, turbidity, and dissolved oxygen. The sampling rate was once per minute for the WQM and once per hour for the other sensors. The participants were: F. Nencioli (FLIP optical package), and F. Spada and G. Chang (hull package and support and trouble-shooting from the KM).

WORK COMPLETED

Data from Scripps Pier and SBC were offloaded from the optical profiler data handler (WET Labs, Inc. DH-4) using WLHost v7.03. The WET Labs, Inc. Automated Processor (WAP) was utilized to extract individual sensor data streams and convert them from raw, binary data into either engineering units (CTD, ac-s, ac-9, ECOs) or ASCII digital counts (LISST). Data extraction and WAPping was performed by F. Spada. Data from the WQM (SBC only) were processed using WQMHostv119a.exe. WQMHost provides final, processed, data with engineering units; no further processing was necessary.

Using The Mathworks Matlab® Software, data processing was completed for all sensors on the optical profiler package. LISST data were processed following the methods described in Agrawal (2005). Filtered ac-9 absorption data, $a_g(\lambda)$, were corrected for the time lag associated with the use of the 0.2 μm filter. All data were binned with depth (10 cm) and with time (1 Hz). Absorption and attenuation data were corrected for instrument drift using measured calibration constants, and temperature and salinity effects following Sullivan et al. (2006) (ac-s) and Pegau et al. (1997) (ac-9). Absorption data were corrected for scattering effects following methods described by Zaneveld et al. (1994). Backscattering coefficients, $b_{bp}(\lambda)$, were computed from the measured volume scattering function using methods presented by Boss and Pegau (2001) and Zhang et al. (2009). The slope of the $c_p(\lambda)$ spectrum, γ, an indicator of particle size distribution, was estimated (Boss et al., 2001) and the real part of the index of refraction of particles, n_p, was derived following methods described by Twardowski et al. (2001). Density, σ_t, was computed from measured temperature and salinity, based on the standard developed by the United Nations. For the SBC only, the mixed layer depth (MLD) was computed

using a 0.5 m temperature criterion. Amanda Whitmire and Scott Freeman are credited for providing several of the subroutines used for data processing.

Concurrent profiles of optical properties collected off the FLIP and the KM during the SBC experiment were analyzed for optical variability. The datasets from the two platforms were merged with depth and density and compared. The ac-s and ECObb-9 measurements from FLIP were interpolated to the KM ac-9 and ECObb-3 wavelengths, respectively. KM profiles were binned to 0.5 m and the profiles measured off FLIP were interpolated to KM depth and σ_t. Percent differences between KM and FLIP measurements were computed according to:

$$\% \text{ Difference} = [\ (X_{KM} - X_{FLIP}) / (X_{KM} + X_{FLIP}) / 2\ ] * 100, \quad (1)$$

where X is temperature, salinity, $a_g(\lambda)$, $a_{pg}(\lambda)$, $c_{pg}(\lambda)$, $b_{bp}(\lambda)$, γ, or n_p as a function of depth and as a function of σ_t ($a_{pg}(\lambda)$ and $c_{pg}(\lambda)$ are the particulate plus dissolved absorption and attenuation coefficients, respectively).

To first-order, we used the relationship presented by Davies-Colley (1988) and further examined by Zaneveld and Pegau (2003) to estimate the horizontal visibility of a black target, y:

$$y = 4.8 / \alpha, \quad (2)$$

where α is the photopic beam attenuation coefficient, which is a function of the spectral background radiance and the distance between the target and the observer. It was approximated by (Zaneveld and Pegau, 2003):

$$\alpha = c_{pg}(532) * 0.9 + 0.081. \quad (3)$$

In this regard, only one of the IOPs, the beam attenuation coefficient at 532 nm, was necessary for predictions of horizontal visibility of a black target. Equations (2) and (3) were applied to IOP data collected during low wind, stratified conditions (< 5 m s^{-1}) and high wind, mixed conditions (≥ 5 m s^{-1}) and examined the differences in predicted visibility

RESULTS

All data were visually inspected for drop-outs, outliers, and errors. Calibration files revealed very little drift of the ac-s a-tube, bb-9, FL-NTU, and LISST. Out of a total of 44 profiles collected at SIO Pier, we had 100% data return for temperature, chlorophyll-a concentration and turbidity, hyperspectral absorption, spectral backscattering, and VSF and PSD. The gain setting on the conductivity sensor was incorrect for the first five casts; hence the first five salinity casts were compromised. The ac-s c-tube drifted severely, at a rate of 0.01 m^{-1} every other day. The ac-s was returned to the manufacturer for repair following the Scripps Pier experiment. The ac-9 a-tube exhibited a drift of about 0.001 m^{-1} every other day at 412, 440, 488, 510, 532, and 555 nm. The red wavelengths drifted more severely, at a rate of about 0.002 m^{-1} every other day. One of the 44 hyperspectral attenuation spectra was not of high quality; the reasons for c-tube failure are unknown (perhaps a clogged tube). Dissolved absorption data were not always of high quality; the 0.2 μm filter clogged quickly. We estimate only 30% data return for $a_g(\lambda)$, mostly from the last 12 files after a fresh filter was installed.

SBC optical profiler data included 15 deep casts and 15 shallow time series. The CTD, ac-9, bb-9, and FL-NTU produced 100% data return. The ac-s a-tube exhibited spectral oscillations that needed to be averaged to produce smooth, accurate spectra; attenuation data were good. The ac-s was again returned for repair following the SBC experiment. The low particle concentrations at the SBC field site contributed to significant noise in the LISST measurements. The LISST is more suitable to particle concentrations of greater than 1 mg L^{-1}. Only data collected following the SBC wind event

were within this range; VSFs and PSDs collected after 17 September were smoother. Additionally, data from the inner rings (> 4°) of the LISST were quite noisy for all casts. Unfortunately, the data handler on the 30 m FLIP package failed immediately (bad cable) and the ac-s and bb-3 did not produce any data.

A diurnal wind pattern was observed during the two-week SBC experiment. Winds were generally calm (< 4 m s^{-1}) in the mornings, and increased to greater than 6 m s^{-1}, oftentimes reaching 10 m s^{-1} by 1600 PDT. Starting on 15 September, winds greater than about 5 m s^{-1} were sustained over the course of two days. The persistent winds resulted in increased upper water column mixing, as evidenced by the increase in 30 m temperature and salinity and the deepening of the mixed layer depth (Figure 5).

Immediately following the high wind event, chlorophyll-a concentration increased from an average of about 1.4 μg L^{-1} to greater than 2 μg L^{-1}. The variability of turbidity closely followed that of chlorophyll-a concentration (Figure 5), indicating that pigmented, organic material (e.g., phytoplankton) dominated the particles at the experiment site. This was confirmed by laboratory analysis of particles in water samples collected off the KM over the duration of the RaDyO experiment (D. Stramski, SIO, pers. comm.).

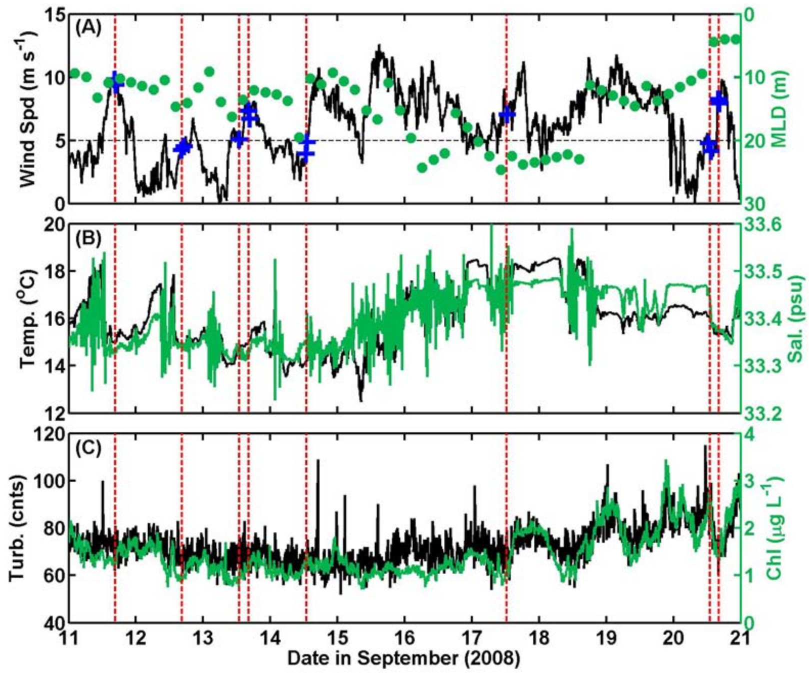

Figure 5. Time series of (A) wind speed (black solid line; 5 m s^{-1} denoted by black dashed line) and mixed layer depth (MLD; green dots) measured/derived off the Kilo Moana, (B) temperature (black) and salinity (green) and (C) turbidity (black) and chlorophyll-a concentration (green) measured at 30 m off the FLIP. The blue crosses and red dashed vertical lines indicate concurrent KM and FLIP sampling periods, respectively. MLD was averaged to 4-hr sampling rate.

The majority of observed hydrographic and optical variability between the KM and FLIP sites of the SBC experiment was found to be the result of platform effects. The hull of the FLIP acted to destroy local stratification during periods when wind speeds were less than 5 m s^{-1}. Differing vertical patterns in hydrographic properties and dissimilar vertical distributions of water constituents (and therefore optical properties) observed between the KM and FLIP were likely the consequence of FLIP-induced

mixing (Figure 6). The FLIP-effect was not a factor during higher wind speeds, as the upper water column was well-mixed. Variability in optical products, γ and n_p, were primarily a consequence of instrumentation effects; the spectral slope of $a_g(\lambda)$ at the KM site was more variable than assumed, which contributed to discrepancies in computed $c_p(\lambda)$, γ, and n_p. It is unlikely that environmental conditions over a horizontal scale of less than 2 km contributed to the consistent observed variability between KM and FLIP hydrographic and optical measurements. The different vertical distributions of IOPs resulted in a 10-57% difference in the range of predicted visibility, with lower percent differences found near the surface and near 30 m and higher differences at intermediate depths (Figure 7).

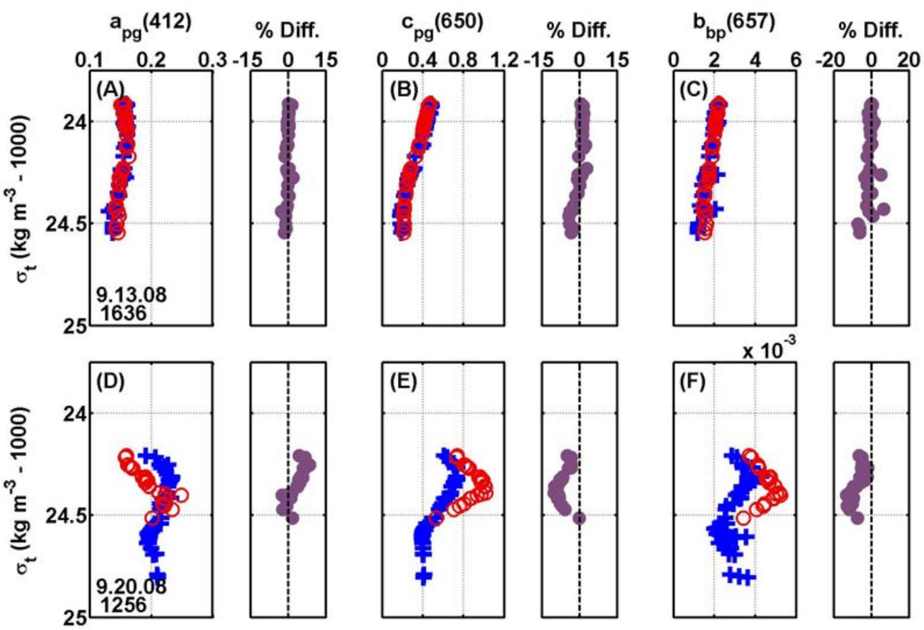

Figure 6. Vertical profiles of optical properties and computed percent differences between Kilo Moana and FLIP measurements as a function of density, σ_t, for (A-C) wind speeds of 6.7 m s^{-1}, measured on 13 September 2008 at 1636 and (D-F) wind speeds of about 4 m s^{-1}, measured on 20 September 2008 at 1256 PDT. Blue crosses represent KM data and red circles denote FLIP data. The units for $a_g(412)$, $a_{pg}(412)$, $c_{pg}(650)$, and $b_{bp}(657)$ are m^{-1}.

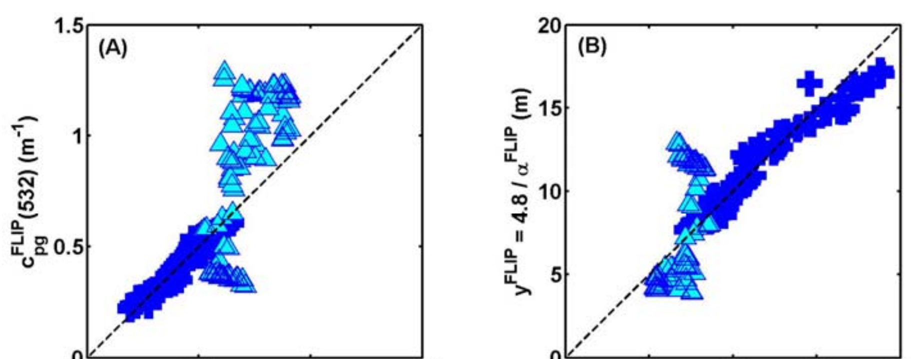

Figure 7. Comparisons between (A) beam attenuation coefficients (532 nm) collected off the Kilo Moana versus those collected off the FLIP and (B) computed horizontal visibility of a black target, y, using data collected off the Kilo Moana versus off the FLIP. Blue crosses and cyan triangles denote data collected during high wind and low wind conditions, respectively.

IMPACT/APPLICATIONS

Our results have the potential to greatly impact the modeling of underwater radiance distribution for the RaDyO project. The hull of FLIP itself has the capability to mix the upper water column and affect SBL processes. Physical measurements conducted by RaDyO PIs off the FLIP are likely compromised. Additionally, IOPs are not being collected off the FLIP during the Hawaii experiment; hence the model(s) will be constructed and/or validated with physical, radiometric, and apparent optical property (AOP) measurements collected off the FLIP and IOP measurements collected off the KM, which is/was several km away.

RELATED PROJECTS

"Prediction of Optical Variability in Dynamic Nearshore Environments," funded by the National Defense Center of Excellence for Research in Ocean Sciences (CEROS), is a related project (PIs: Chang, Jones, Hansen, Twardowski, and Barnard). The objective of this project is to develop a system for forecasting marine optical conditions in the surf zone for the purpose of improving Naval operations. With our in situ optical forecast model, the Navy Fleet will be able to deploy remote drifters, combine drifter data with meteorological and oceanographic data within our model, and predict optical properties along a coastline of interest.

In order to reach our objectives, numerical wave and hydrodynamic models will be developed and validated with field measurements obtained by moored platforms, vertical profilers, and optical drifters in two surfzone environments: Santa Cruz, CA and Waimanalo, HI. Physical and optical characterization will be conducted on multiple temporal and spatial scales spanning a wide dynamic range of conditions to demonstrate the validity of the system.

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